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SEDIMENT STUDIES IN BACK RIVER ESTUARY, BALTIMORE, MARYLAND

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The report is an investigation of the Back River Estuary located in Maryland. The study objectives were: determine in-situ sediment oxygen demand rates of the surficial bottom deposits; determine the general distribution and approximate depth of organic sludge deposits; compare the sediment oxygen demand of surficial to underlying sediments; determine existing nutrient concentrations of surficial and subsurface sediments; evaluate the Maryland Water Resource Authority engineering proposals for improving the water quality of the Back River Estuary.

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ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF ENFORCEMENT

SEDIMENT STUDIES IN BACK RIVER ESTUARY
BALTIMORE, MARYLAND

April 1976

National Enforcement Investigations Center - Denver, Colorado
Region III - Philadelphia, Pennsylvania
Maryland Water Resources Administration

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I. INTRODUCTION

The Baltimore Back River Waste Water Treatment Plant (WWTP), built in the early 1900's, normally discharges approximately 230,000 to 300,000 m^3/day (60 to 80 mgd) of secondary treated wastewater into the Back River Estuary. In addition, a minimum of 380,000 m^3/day (100 mgd) of secondary treated wastewater is directed to the Bethlehem Steel Company for use as process water. Subsequently, this process water is discharged by the Bethlehem Steel Company into Baltimore Harbor.

The NPDES* permit conditions are based on the assumption that the WWTP can effectively treat a total discharge not exceeding approximately 680,000 m^3/day. Consistent hydraulic overloading (more than 680,000 m^3/day) has frequently occurred in recent years.

The Maryland Water Resources Administration (MWRA) has reported that water quality of the Back River Estuary has been degraded by the discharge from the hydraulically overloaded WWTP. Settleable solids contained in the effluent as well as algae biomass have caused the accumulation of 1 to 1.5 m of unconsolidated organic sludge on the bottom of the estuary. The discharge of nutrient-rich wastewater from the WWTP has stimulated algal blooms during the summer, and associated dissolved oxygen depressions have resulted in massive fish kills.

A number of programs have been proposed by the MWRA to improve water quality in the Back River Estuary. The alternatives include the relocation of the WWTP outfall nearer the mouth of the estuary where

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* *National Pollutant Discharge Elimination System*

flushing rates are greater, or discharge the treated wastewater directly into Chesapeake Bay. In addition, it may be necessary to initiate nutrient removal at the WWTP. These proposals do not account for the nutrient loading potential and the sediment oxygen demand (SOD) exerted by existing sludge deposits. Preliminary modeling analysis by the MWRA assumes that current sediment accumulations exert a sediment oxygen demand of 1 to 3 grams $O_2/m^2/day$; such rates could consume a major portion of the available dissolved oxygen in the estuary. Therefore, removal of sediments by dredging may be required to insure improvement of the water quality in the estuary.

The MWRA has estimated removal of 8.0 million m^3 of surficial sediments by dredging would cost about $50 million. The success of a dredging program is unknown because little is known about the SOD and nutrient exchange characteristics of the underlying sediment. Thus, it was necessary to conduct a study to compare SOD rates and nutrient interchange characteristics of surficial and underlying sediments before a decision on dredging could be made. All pertinent construction at the Baltimore Back River WWTP and related planning by the Maryland WRA has been postponed pending completion of these required studies.

EPA Region III, on July 14, 1975, requested that the NEIC conduct an investigation of the Back River Estuary. Study objectives were:

1. Determine in-situ sediment oxygen demand rates of the surficial bottom deposits.

2. Determine the general distribution and approximate depth of organic sludge deposits.

3. Compare the sediment oxygen demand of surficial to underlying sediments.

4. Determine existing nutrient concentrations of surficial and subsurface sediments, and characterize the sediment to water nutrient exchange rates as influenced by aerobic and anoxic conditions.

5. Evaluate the Maryland WRA engineering proposals for improving the water quality of the Back River Estuary.

II. SUMMARY AND CONCLUSIONS

1. Organic sludge deposits ranging from 1 to 1.5 m thick exist in portions of the Back River Estuary.

2. Surficial sediments composed of organic sludge exert a high sediment oxygen demand on the estuary, contributing to chronic conditions of dissolved oxygen depression.

3. Dredging the major portion of the estuary would not be practical because of high SOD of the underlying sediments and the relative isolation of sludge deposits in deep water channels. Although sludge deposits were uniformly distributed at stations 1 to 4 and dredging could reduce SOD, increased water depths in this area could lead to stagnation.

4. Surficial sediments throughout the estuary contained higher concentrations of inorganic nitrogen and phosphorus than the underlying sediments.

5. Surficial sediments leached about 50% more inorganic nitrogen into the water column than the underlying sediments either aerobically or anoxically. Under aerobic conditions, underlying sediments released approximately 200% more phosphorus and 500% more orthophosphate than surficial sediments. The nutrient exchange rate for phosphorus and orthophosphate under anoxic conditions was greater from surficial sediments by averages of approximately 60% and 100%.

6. If aerobic conditions are maintained in the water column, dredging of surficial sediments would not substantially lower the algal growth potential of the Back River Estuary. Under anoxic conditions,

phosphorus contribution to the water column from either surficial or underlying sediments could stimulate algal growth.

7. Diversion of the Baltimore Back River WWTP effluent would reduce nutrient loading in the estuary. For an undetermined period, nutrients would continue to leach from the existing sediments into the overlying water of the Back River Estuary. Time requirements have not been estimated for a stable sediment bed to be established in the estuary.

III. RECOMMENDATIONS

1. To reduce sludge deposits the Baltimore Back River WWTP should be upgraded to meet NPDFS settleable solids requirements for secondary treatment of wastewater.

2. Dredging the Back River Estuary could double the present volume of water and create conditions conducive to stagnation. Plans for selective removal of surficial sediments should be made after the results of natural stabilization of the sludge deposits are known.

IV. STUDY AREA

The Back River is a shallow, turbid, slow-moving river located in north central Maryland. Before it discharges into the southwest end of Hawk Cove, it forms the Back River Estuary. "Back River Estuary" as used throughout this report refers to the terminal 12 km of the Back River extending from the Eastern Avenue Bridge to the mouth at Rocky Point [Fig. 1]. The estuary has a mean depth of 1.4 m and, in the upper reaches, velocities of less than 0.1 m/sec are common. The entire study area is under tidal influence having a mean range of about 0.3 m (1 ft). Prolonged winds of constant direction may cause substantial variation in tide.

Field investigations of the Back River Estuary were conducted by NEIC from August 21-27, 1975. Twelve sampling stations were selected to correspond with existing sites presently being used by the Maryland Water Resources Administration [Table 1]. Stations 1 and 2 are upstream of the Baltimore Back River WWTP point of discharge which is near the mouth of Bread and Cheese Creek. Stations 3 through 10C extend along the estuary from the WWTP discharge downstream to Rocky Point. Sediment oxygen demand studies were performed at all twelve locations. Tests to determine the sediment to water nutrient exchange characteristics were done only at stations 1 through 10A.

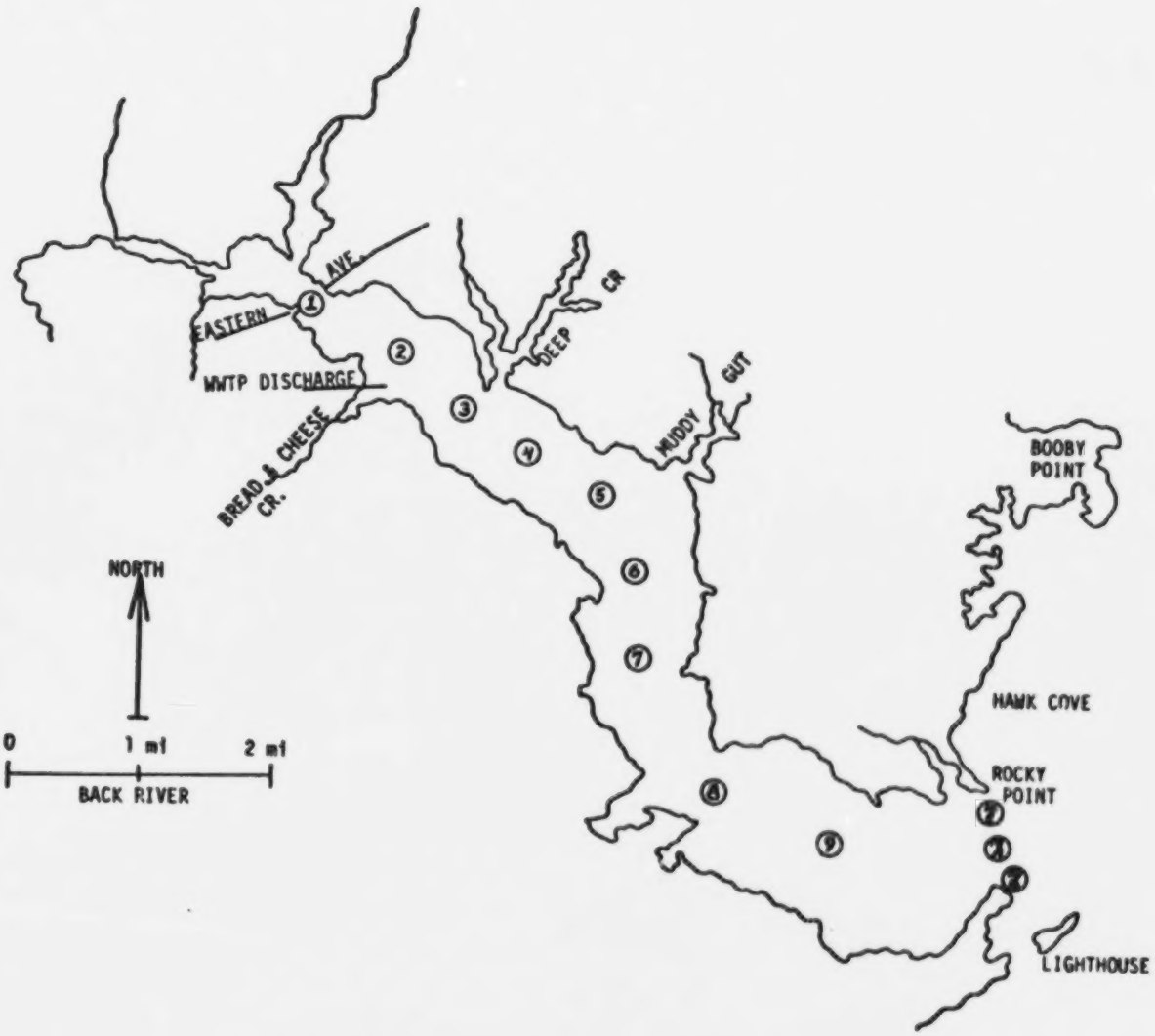

Figure 1. Sampling Locations - Back River Estuary
Baltimore, Maryland - August 1975

Table 1

SAMPLE LOCATIONS
BACK RIVER ESTUARY - BALTIMORE, MARYLAND
August 1975

Station		Description
1	Mid-channel	7.2 river miles upstream from mouth of Estuary at Rocky Point
2	Mid-channel	6.4 river miles upstream from mouth
3	Mid-channel	5.6 river miles upstream from mouth
4	Mid-channel	5.2 river miles upstream from mouth
5	Mid-channel	4.9 river miles upstream from mouth
6	Mid-channel	4.2 river miles upstream from mouth
7	Mid-channel	3.1 river miles upstream from mouth
8	Mid-channel	2.2 river miles upstream from mouth
9	Mid-channel	0.9 river miles upstream from mouth
10A	Mid-channel	At Rocky Point
10B	Quarter-channel	Quarter-channel off Lighthouse
10C	Quarter-channel	Quarter-channel off Rocky Point

V. RESULTS AND DISCUSSION

The general distribution and approximate depth of organic sludge deposits in the Back River Estuary were established by core sampling. Samples were taken at stations 1 through 10A at mid-channel [Fig. 1]. Additional observations were made from mid-channel toward each bank to determine the lateral distribution of sludge deposits. The bottom of half of the estuary (stations 1 through 7) was uniformly covered by a 1 to 1.5 m layer of black, gelatinous, organic sludge. An odor of hydrogen sulfide was detectable. The underlying sediment layer throughout this area consisted of a fine-particulate, dense, gray clay-like material of undetermined thickness. No particular odor was associated with the underlying layer. Stratification was very distinct with a small (20 to 30 cm) transitional area of softer clay-like material separating the two sediment layers.

The lower reach of the estuary, downstream from station 8, differed in character in that sludge deposits were restricted to the main channel and isolated depressions. Stratification in these areas was similar to that found in the upper half of the estuary. Core samples collected in the shallow water near both banks contained coarse sand.

IN-SITU SEDIMENT OXYGEN DEMAND TESTS

Sediment oxygen demand (SOD) tests were conducted at ten sampling sites along a mid-channel line. Two additional tests were performed halfway from mid-channel to either shore at stations 10B and 10C. The SOD rates could not be estimated at stations 3 and 4 because dissolved oxygen levels in the overlying water were depressed (3.4 and 2.8 mg/l, respectively).

The SOD for the western portion of the estuary (stations 1, 2, 5, 6) averaged 5.5 g $O_2 m^2$/day (range 4.8-6.2) as opposed to an average of 3.7 g O_2/m^2/day (range 1.9-5.1) at stations 7, 8, 9, 10A, 10B, and 10C [Table 2, Fig. 2]. The SOD rate for an undisturbed silt or clay river bed would not be expected to exceed 2 g O_2/m^2/day, whereas, rates ranging from 4.8 to 6.1 g O_2/m^2/day have been reported for sewage sludge.[1] All sites in the western half of the estuary had SOD rates indicative of sewage sludge. The average SOD rate of 3.7 g O_2/m^2/day for the eastern half of the estuary indicated that this area was also affected by wastewater deposits but to a lesser degree.

The combined effect of shallow water, low-flushing potential, and high SOD rates in surficial sediments in the western portion of the estuary is a principal cause of the dissolved oxygen depressions historically common to this area. Although the average SOD of 3.7 g O_2/m^2/day in the eastern half of the estuary was high, this area is better able to assimilate a high SOD with less apparent deleterious effect on the environment. The sludge deposits are more confined to the deep water channels, the flushing rates are more efficient due to tidal influence, and there is a greater overall water volume.

In addition to in-situ SOD studies, a series of laboratory tests were conducted to compare SOD rates of surficial sludge deposits with the underlying sediment layer. At all stations, surficial sludge deposits exerted a higher SOD than the underlying sediments [Table 2, Fig. 3]. The SOD rates for surficial sediments were high throughout the entire length of the estuary. However, only at stations 1 through 4 was the SOD of underlying sediments substantially lower than the SOD of the surficial sediments. Removal of surficial sediments as an attempt to reduce SOD is practical for only about 37% of the estuary (stations 1 through 4). However, because of the low flushing rate in this area, dredging is not advisable. Removal of 1 to 1.5 m of surficial sediments would at least double the water depth of this section of the estuary, creating conditions conducive to stagnation.

Table 2

SEDIMENT OXYGEN DEMAND[†]
BACK RIVER ESTUARY - BALTIMORE, MARYLAND
August 1975

Station	In Situ	Laboratory Test	
		Surface Sediment	Underlying Sediment
1	4.8	11.0	2.4
2	6.2	9.8	2.4
3		4.1	1.0
4		9.8	1.2
5	5.4	7.7	6.5
6	5.6	9.8	4.3
7	1.9	11.0	6.7
8	4.7	12.2	4.9
9	4.3	9.2	7.3
10A	3.1	11.0	6.1
10B	3.1		
10C	5.1		

† *All values expressed as grams* $O_2/m^2/day$

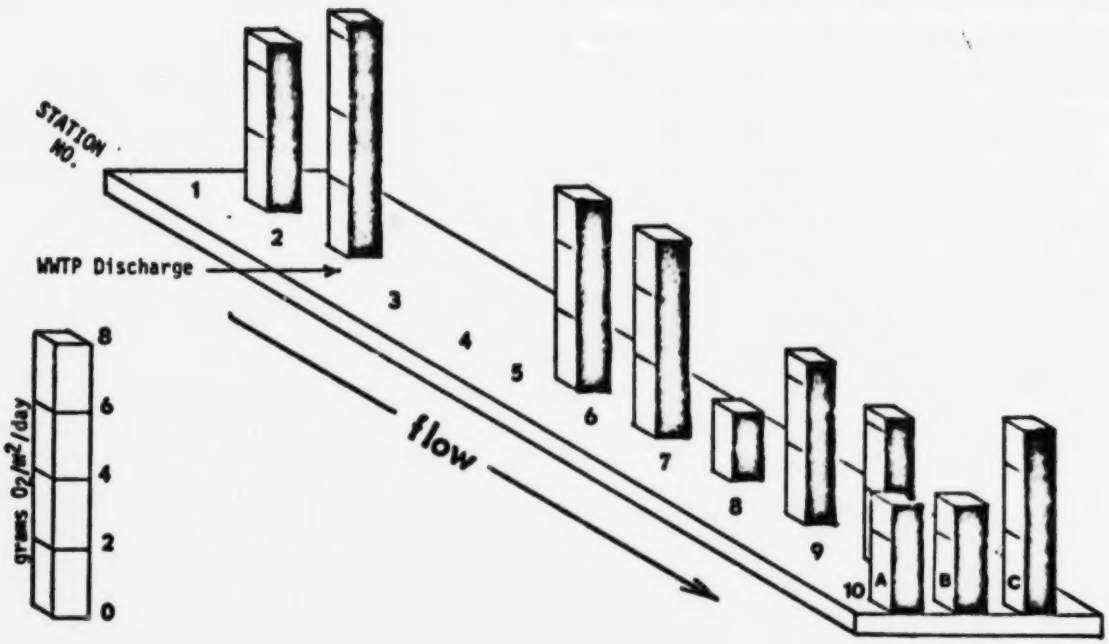

Figure 2. In-Situ Sediment Oxygen Demand

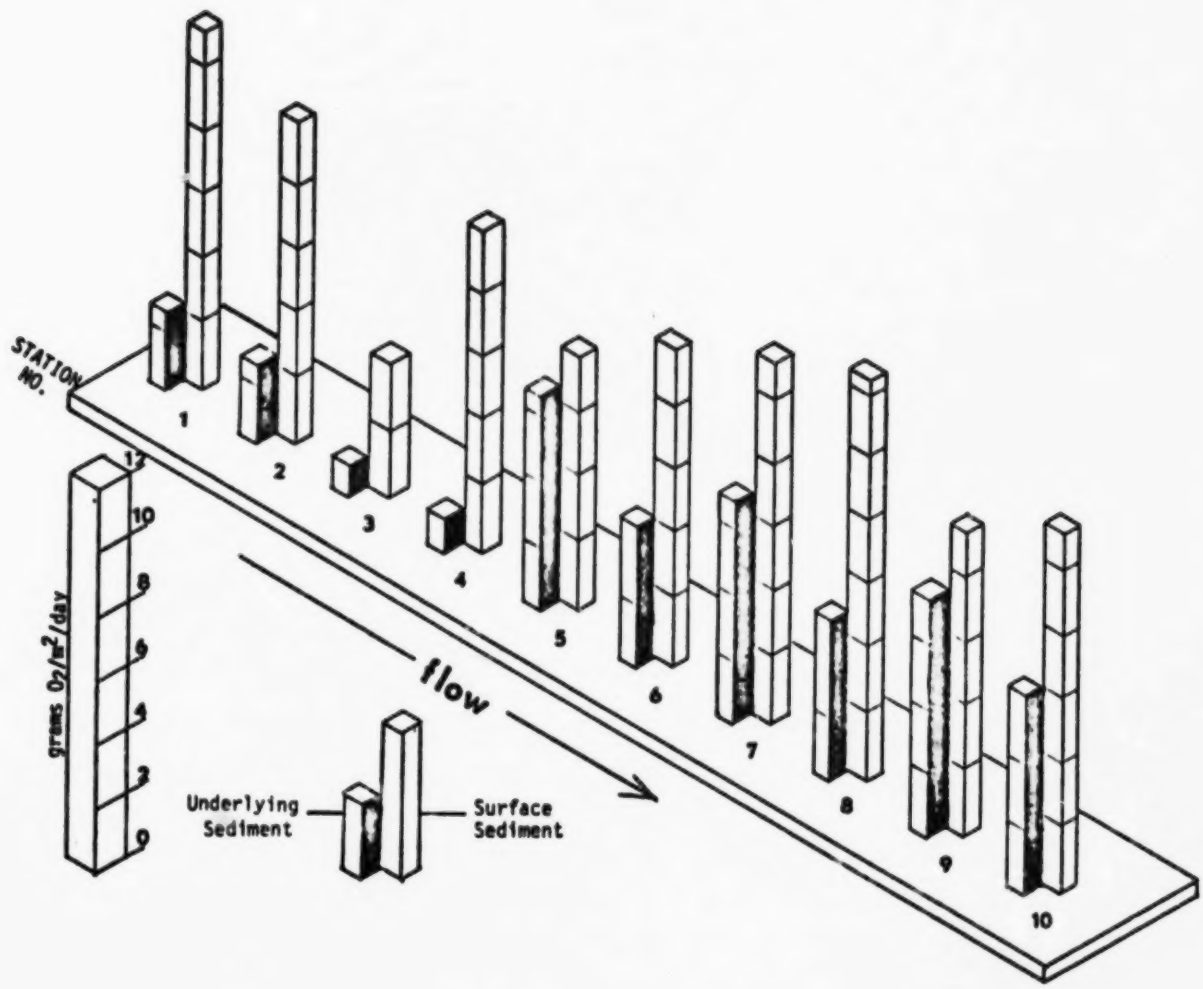

Figure 3. Sediment Oxygen Demand Laboratory Test

NUTRIENT INTERCHANGE

The rate at which nutrients (NO_2, NO_3, NH_3, orthophosphate, and total phosphorus) are released from the sediment to the water column constitutes a major factor regulating the algal growth potential of this system. Core samples were taken at ten stations; surficial and underlying sediments were analyzed to assess the potential of each layer for nutrient loading to the water column.

Of the nitrogenous fraction of the nutrient load (NO_2, NO_3, NH_3), ammonia (NH_3) was dominant [Table 3], averaging 93.7 and 91.4% of the total inorganic nitrogen (NO_2 + NO_3 + NH_3) in surficial and underlying sediments, respectively.* The remaining nitrogen load was primarily nitrate (NO_3) averaging 5.7 and 7.3% in surficial and underlying sediments. Nitrite (NO_2) was the least significant nitrogen component, comprising only about 1% in either surficial or underlying sediment layers.

Because most algae possess the capability of using all three nitrogen fractions (NO_2, NO_3, NH_3), it is convenient to use total inorganic nitrogen values (NO_2 + NO_3 + NH_3) for comparative analyses of growth potential.

Total inorganic nitrogen in surficial and subsurface sediments averaged 549.8 and 318.6 mg/kg, respectively [Table 3]. The surficial sediments at stations 1 to 7 averaged 77% (range 27-121%) higher concentrations of total inorganic nitrogen than the underlying sediment samples [Fig. 4]. At station 8, the surficial sediment concentration was 299% higher than subsurface sediments, while at station 9 total

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* *The underlying sediment obtained at station 10 consisted primarily of sand. Nutrient values differed significantly from underlying samples at all other stations and were not used for averages or comparative values in this section of the report.*

Table 3

NUTRIENT CONCENTRATION IN SEDIMENT SAMPLES†
BACK RIVER ESTUARY - BALTIMORE, MARYLAND
August 1975

Station	NO_2	NO_3	NH_3	Total Inorganic Nitrogen	Total Phosphorus	Ortho-phosphate
1						
Surface	2.94	5.88	772.6	781.4	3,966	143.9
Underlying	1.67	78.20	455.1	535.0	2,758††	47.5
2						
Surface	2.61	39.10	817.0	858.7	5,435	178.1
Underlying	1.45	7.27	424.3	433.0	637	36.4
3						
Surface	3.77	42.40	588.5	634.7	4,063	207.1
Underlying	10.90	83.20	252.4	346.5	826	83.2
4						
Surface	2.37	4.74	535.8	542.9	3,912	218.1
Underlying	1.07	8.04	235.8	244.9	705	109.9
5						
Surface	4.68	7.20	407.1	419.0	1,981	97.3
Underlying	9.99	13.50	305.0	328.5	575	64.8
6						
Surface	3.13	26.80	617.4	647.3	4,026	127.2
Underlying	1.82	7.81	424.5	434.1	-	72.9
7						
Surface	3.12	70.10	389.6	462.8	5,018	85.7
Underlying	1.77	7.57	204.5	213.8	727	83.3
8						
Surface	3.09	58.10	534.3	595.5	3,244	85.1
Underlying	2.01	6.69	140.6	149.3	781	69.2
9						
Surface	1.80	23.10	162.3	187.2	2,383	72.1
Underlying	1.83	15.70	164.5	182.0	914	80.9
10						
Surface	2.25	3.21	363.3	368.8	1,849	99.7
Underlying††	0.13	11.70	7.8	19.6	97.2	6.5
Mean Surface	2.98	28.1	518.8	549.8	3,588	131.4
Range	1.80-4.68	3.21-70.10	162.3-817.0	187.2-858.7	1,849-5,435	72.1-218.1
Mean Underlying	3.61	25.3	289.6	318.6	737.8	72.0
Range	1.07-10.90	6.69-83.2	140.6-455.1	149.3-535.0	575-914	36.4-109.9

† *All values expressed as mg/kg*
†† *These values not included in averaging or range*

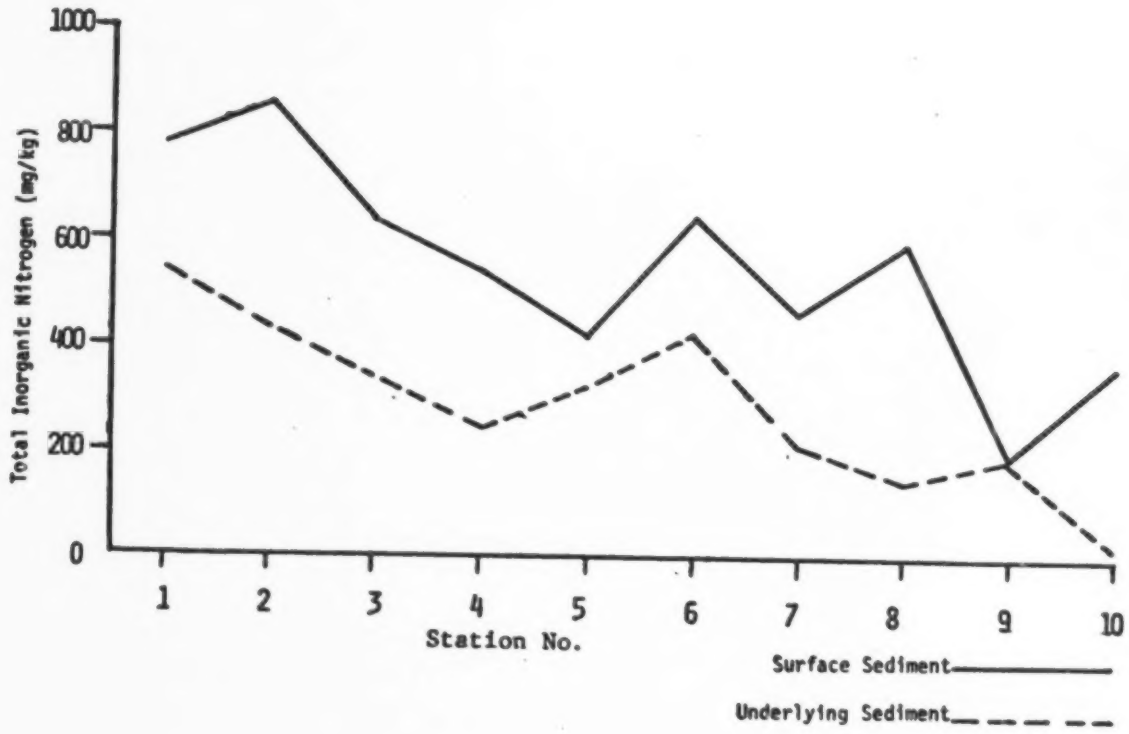

Figure 4. Core Sample - Total Inorganic Nitrogen

inorganic nitrogen was essentially the same, the surface sediment concentration being only 2.8% greater. The overall trend was toward a gradual decrease in total inorganic nitrogen from the western sector to the mouth of the estuary both in surficial and underlying sediments.

Total phosphorus in surficial sediments was high, averaging 3,588 mg/kg; the range for all stations was from 1,849 to 5,435 mg/kg [Table 3]. Typical lake sediments contain total phosphorus levels of 1,000 to 2,000 mg/kg.[2] High phosphorus levels in surficial sediments are generally associated with wastewater treatment plant discharges. Underlying sediments for the major portion of the estuary (stations 2, 3, 4, 5, 7, 8, 9) had phosphorus concentrations averaging 737.8 mg/kg.* Without exception, surficial sediments contained greater levels of total phosphorus averaging 416% (range 161-753%) higher than underlying sediments [Fig. 5].

Orthophosphate is of particular interest because it is the form of phosphorus most easily used by algae. In general, surficial sediments had higher concentrations of orthophosphate [Fig. 6], averaging 131.4 mg/kg as opposed to only 72.0 mg/kg for underlying sediments [Table 3]. From stations 5 to 9, surficial sediments had orthophosphate levels averaging 28% greater than subsurface sediments; whereas, surficial sediments in the area of stations 1 to 4 had an average of 210% more orthophosphate than did underlying sediments. The increased level of orthophosphate at stations 1 to 4 corresponded to an area of known excessive algal bloom and low dissolved oxygen.

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* *The underlying sediment sample at station 1 had a phosphorus concentration of 2,758 mg/kg. This value was significantly higher than phosphorus concentrations in the underlying sediments at all other stations. For this reason, and because of the close proximity of station 2 which had a lower value, this value was not included in the average. No value was available for station 6.*

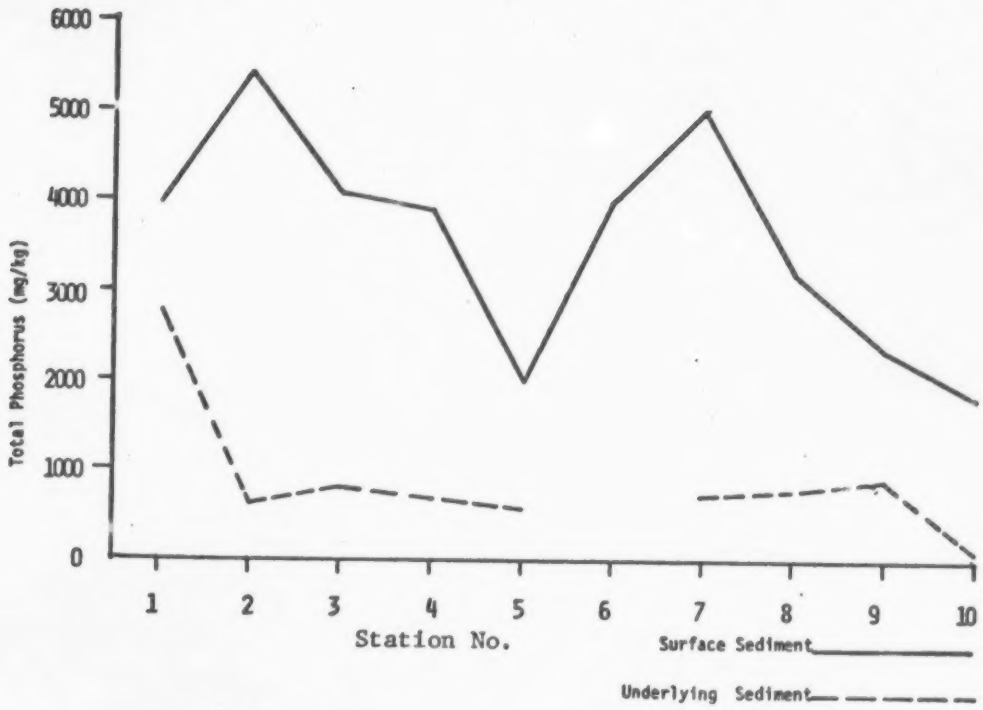

Figure 5. Core Sample - Total Phosphorus

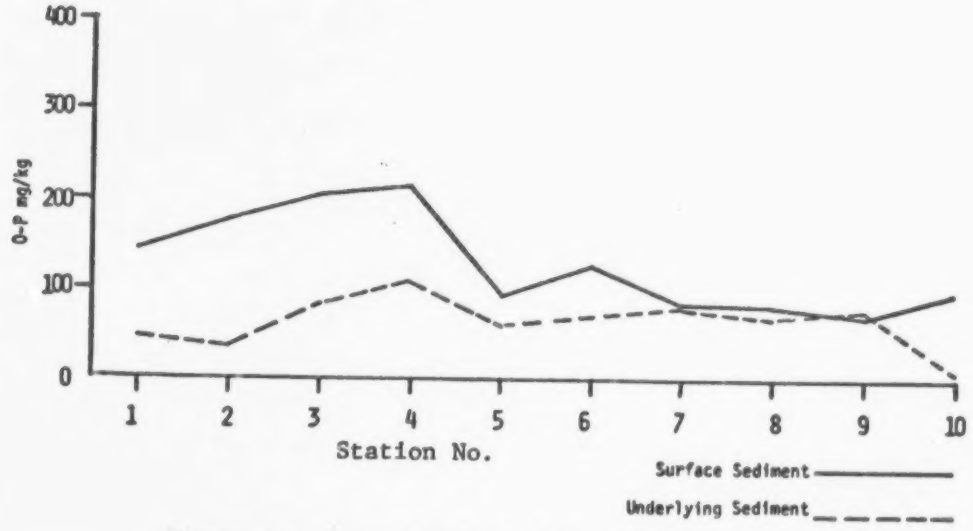

Figure 6. Core Sample - Orthophosphate

In general, these studies show that existing surficial sediments have higher nutrient concentrations than do underlying sediments. This does not imply, however, that underlying sediments, if directly exposed to the water column as the result of dredging, would be less capable of leaching nutrients into the water column than are existing surficial sediments. Tests to determine nutrient interchange characteristics from surficial and underlying sediment layers into the water column were performed using materials from the same core samples initially analyzed for nutrient concentrations. The release of nitrogen from the sediment to the water column is controlled by microorganisms, particularly bacteria, which transform organic nitrogen to soluble forms such as ammonia and nitrate.

The interchange of ammonia from sediments into the water column was shown to be independent of the oxygen state of the system; a net increase in ammonia concentration was observed in all samples either aerobic or anoxic [Figs. 7, 8]. The anoxic systems averaged final net concentrations of ammonia 28% higher than aerobic systems. However, this probably reflects a physical loss of ammonia to the atmosphere resulting from aeration of aerobic systems, as well as conversion of ammonia to nitrate and nitrite, rather than indicating that anoxic systems were more efficient ammonia generators.

With only one exception (surficial sediment at station 3), aerobic conditions resulted in net increases of nitrate (NO_3) and nitrite (NO_2) concentrations in the water column. The net increase in nitrite for all samples averaged 0.62 mg/l while nitrate increases averaged 2.1 mg/l [Table 4]. This indicated nitrification was occurring in the aerobic water column with nitrite appearing as an intermediate step in the complete nitrification of ammonia to nitrate.

Without exception, anoxic conditions resulted in a small net decrease in nitrate and nitrite concentrations [Table 4]. This indicated

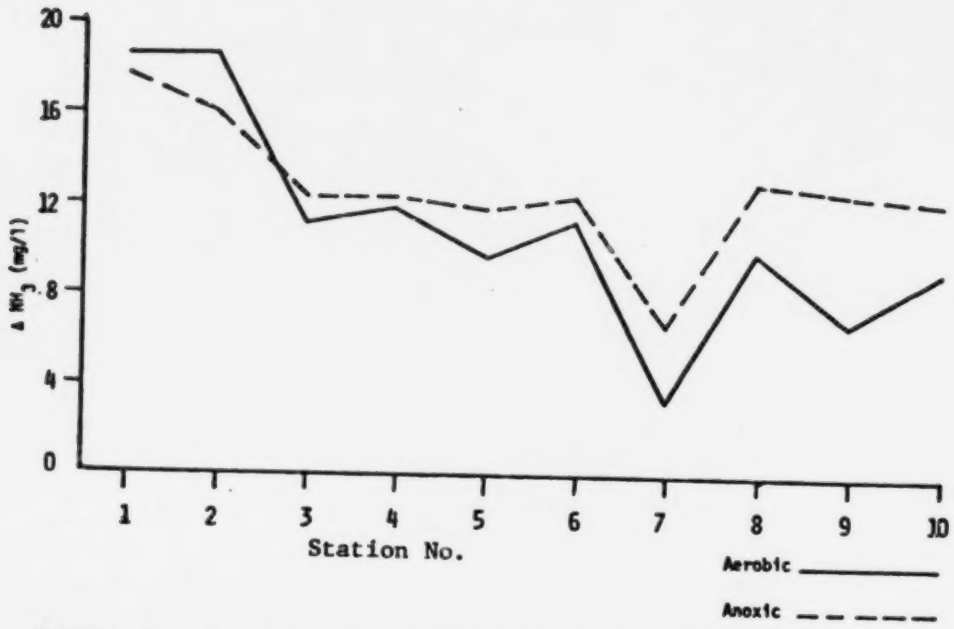

Figure 7. Surface Sediment Nutrient Exchange Δ Ammonia
6-day exposure

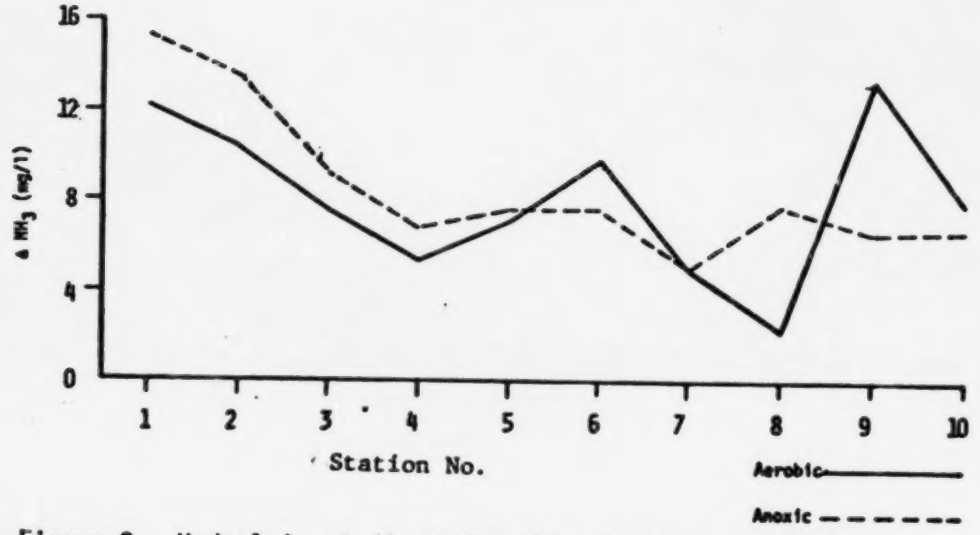

Figure 8. Underlying Sediment Nutrient Exchange Δ Ammonia
6-day exposure

Table 4

NUTRIENT INTERCHANGE BETWEEN SEDIMENT AND WATER†
BACK RIVER ESTUARY - BALTIMORE, MARYLAND
August 1975

Station	NO_2 Aerobic	NO_2 Anoxic	NO_3 Aerobic	NO_3 Anoxic	NH_3 Aerobic	NH_3 Anoxic	Total Inorganic Nitrogen Aerobic	Total Inorganic Nitrogen Anoxic	Total Phosphorous Aerobic	Total Phosphorous Anoxic	Orthophosphate Aerobic	Orthophosphate Anoxic
1												
Surface	0.81	-0.12	0.13	-0.06	18.15	17.64	19.09	17.64	-0.12	0.26	-0.09	0.36
Underlying	1.14	-0.12	4.85	-0.06	12.15	15.44	18.14	15.44	-0.16	0	-0.16	0.13
2												
Surface	0.70	-0.10	0.59	-0.08	18.15	15.94	19.44	15.94	-0.04	0.58	-0.04	0.64
Underlying	0.75	-0.10	1.35	-0.03	10.35	13.64	12.45	13.64	-0.12	-0.02	-0.09	0.11
3												
Surface	0.56	-0.12	-0.05	-0.06	11.05	12.14	11.61	12.14	-0.08	0.54	-0.01	0.61
Underlying	0.58	-0.10	1.18	-0.04	7.65	8.64	9.41	8.64	0.24	0.28	0.26	0.41
4												
Surface	0.58	-0.12	0.01	-0.02	11.65	12.14	12.24	12.14	-0.04	1.06	0.03	0.96
Underlying	0.64	-0.08	3.37	-0.02	5.25	6.84	9.26	6.84	0.44	0.62	0.39	0.71
5												
Surface	0.58	-0.12	1.85	-0.02	9.45	11.54	11.88	11.54	0.12	0.94	0.09	0.91
Underlying	0.58	-0.05	1.77	-0.08	7.05	7.64	9.40	7.64	0.24	0.46	0.21	0.56
6												
Surface	0.58	-0.04	1.52	-0.05	11.05	12.14	13.15	12.14	-0.08	0.46	-0.04	0.59
Underlying	0.61	-0.04	3.00	-0.05	9.75	7.64	13.36	7.64	0.20	0.34	0.21	0.44
7												
Surface	0.70	-0.05	4.73	-0.08	2.85	6.34	8.28	6.34	0.16	1.74	0.11	1.24
Underlying	0.48	-0.05	1.96	-0.08	4.75	5.04	7.19	5.04	0.48	0.78	0.44	0.74
8												
Surface	0.65	-0.08	3.79	-0.06	8.85	12.84	13.29	12.84	0.04	0.74	0.04	0.76
Underlying	0.54	-0.07	0.73	-0.06	2.15	7.74	3.42	7.74	0.08	0.62	0.11	0.71
9												
Surface	0.61	-0.04	4.48	-0.05	6.25	12.34	11.34	12.34	0.36	0.78	0.31	0.86
Underlying	0.48	-0.10	0.83	-0.04	13.25	6.54	14.56	6.54	0.30	0.78	0.37	0.66
10												
Surface	0.75	-0.10	5.36	-0.04	8.75	11.34	14.86	11.94	0	0.62	-0.04	0.74
Underlying	0.06	-0.11	0.21	-0.02	7.75	6.64	8.02	6.64	0.02	0.50	0.09	0.51
Mean Surface	0.65	-0.09	2.25	-0.05	10.6	12.5	13.52	12.5	0.03	0.77	0.04	0.77
Range	0.56-0.81	-0.12--0.04	-0.05-5.36	-0.08--0.02	2.85-18.15	6.34-17.64	8.28-19.44	6.3-17.6	-0.12-0.36	0.26-1.74	-0.09-0.31	0.36-1.24
Mean Underlying	0.59	-0.08	1.90	-0.05	8.0	8.6	10.5	8.6	0.17	0.45	0.18	0.50
Range	0.06-1.14	-0.12--0.04	0.21-4.85	-0.08--0.02	2.15-13.25	5.04-15.44	3.42-18.14	5.04-15.44	-0.16-0.48	-0.02-0.78	-0.16-0.44	0.13-0.74

† *All values represent mg/l net nutrient exchange into the water column for 6-day exposure*

that anoxic conditions were maintained in these systems and no oxygen was available to permit conversion of ammonia to an oxidized nitrogen state. The slight loss of nitrate and nitrite is attributable to bacterial metabolism as well as to the ability of these compounds to revert to ammonia under anoxic conditions.

It is apparent that of the three nitrogenous compounds (NO_2, NO_3, NH_3) only ammonia leached directly from the sediments. Nitrite and nitrate were present initially in all sediment samples [Table 3]; the fact that these compounds were found only in the water column of aerobic samples confirms the supposition that they were generated in the water column and did not interchange from the sediment bed.

The comparison of the nitrogenous interchange potential of surficial and underlying sediments is most clearly demonstrated by net ammonia and total inorganic nitrogen concentrations. Total inorganic nitrogen levels were consistently higher in waters exposed to surficial sediments either aerobically (50.2%) or anoxically (51.9%) [Figs. 9, 10 and Table 4]. These trends are consistent with the sediment nutrient analyses which indicated total inorganic nitrogen levels about 77% greater in surficial sediments. Ammonia interchange rates were essentially the same. Surficial sediments released the greater quantities of nutrient aerobically and anoxically by 48.4 and 51.9%, respectively [Table 4].

The relationship between phosphorus and sediments is complex; however, certain concepts are generally accepted. Two closely related factors play a major role in controlling chemical and physical mobility of phosphorus for a given sediment type. Oxidation-reduction potential controls the oxidation state of iron thereby affecting the ability of sediments to retain or release inorganic phosphorus.[2] In an aerobic system, phosphorus is strongly bound to Fe^{+3} and little or no dissolved inorganic phosphorus will be released from the sediments.[3,4] Under anoxic conditions, iron will revert to the reduced form (Fe^{+2}) and

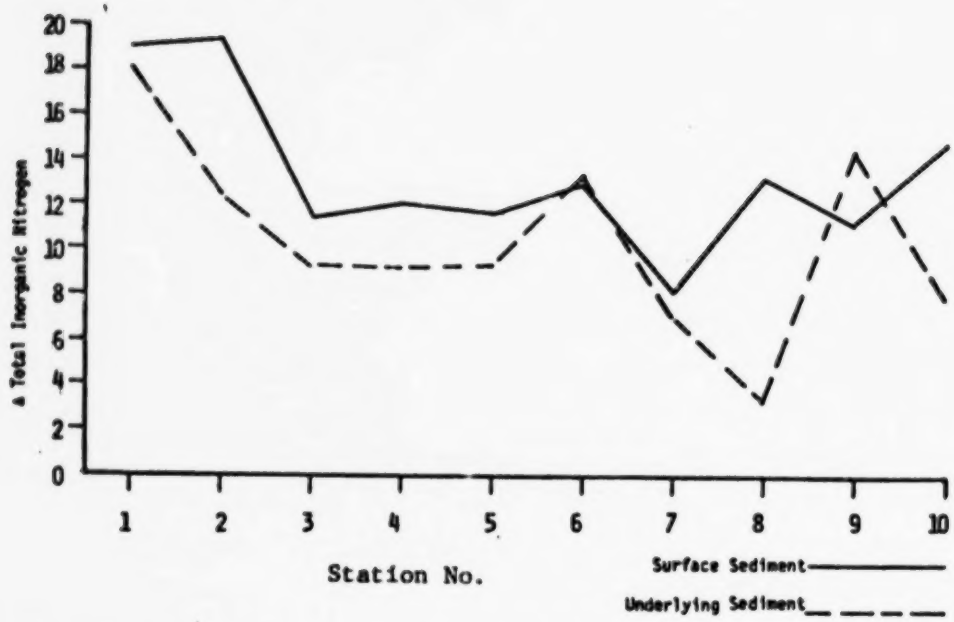

Figure 9. Aerobic Nutrient Exchange Δ Total Inorganic Nitrogen
6-day exposure

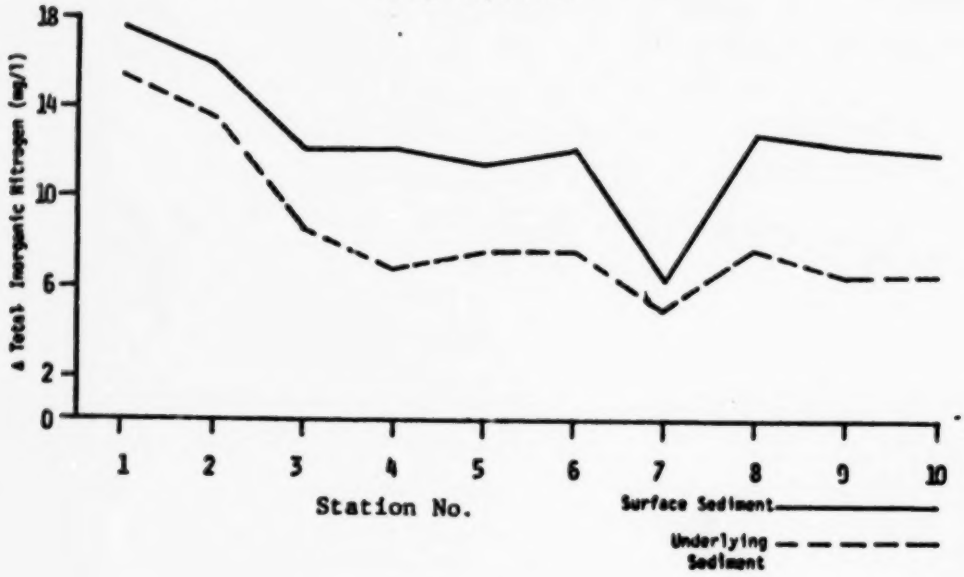

Figure 10. Anoxic Nutrient Exchange Δ Total Inorganic Nitrogen
6-day exposure

orthophosphate will be released into the interstitial water (water filling the spaces between sediment particles). Interstitial water may contain orthophosphate concentrations 50 times greater than those found in the overlying water column.[2] The transport of phosphorus from interstitial water into the water column is dependent on diffusion rate and the extent of turbulent mixing.[2]

Concentrations of phosphorus and iron in surface sediments have been reported to increase with increasing depth of the overlying water column.[5] Apparently, phosphorus preferentially associates with fine textured, low-density particles that tend to settle slowly from the water column. This trend was noted in the analyses of surficial sediments [Table 3] where phosphorus levels remained relatively high in deeper waters near the mouth of the estuary.

Phosphorus migration in the laboratory tests corresponded exactly with classical predictions; 6-day net concentrations in the anoxic systems averaged approximately 700% greater for total phosphorus [Figs. 11, 12] and 1,000% greater for orthophosphate than in the respective aerobic systems [Table 4]. These data show increasing phosphorus levels were due almost entirely to orthophosphate migration as final net averages for total phosphorus and orthophosphate are nearly the same.

Surface Sediment	Aerobic	Anoxic
	T-P 0.03 mg/l	T-P 0.77 mg/l
Average final net concentration	O-P 0.04 mg/l	O-P 0.77 mg/l
Underlying Sediment		
	T-P 0.18 mg/l	T-P 0.45 mg/l
Average final net concentration	O-P 0.17 mg/l	O-P 0.49 mg/l

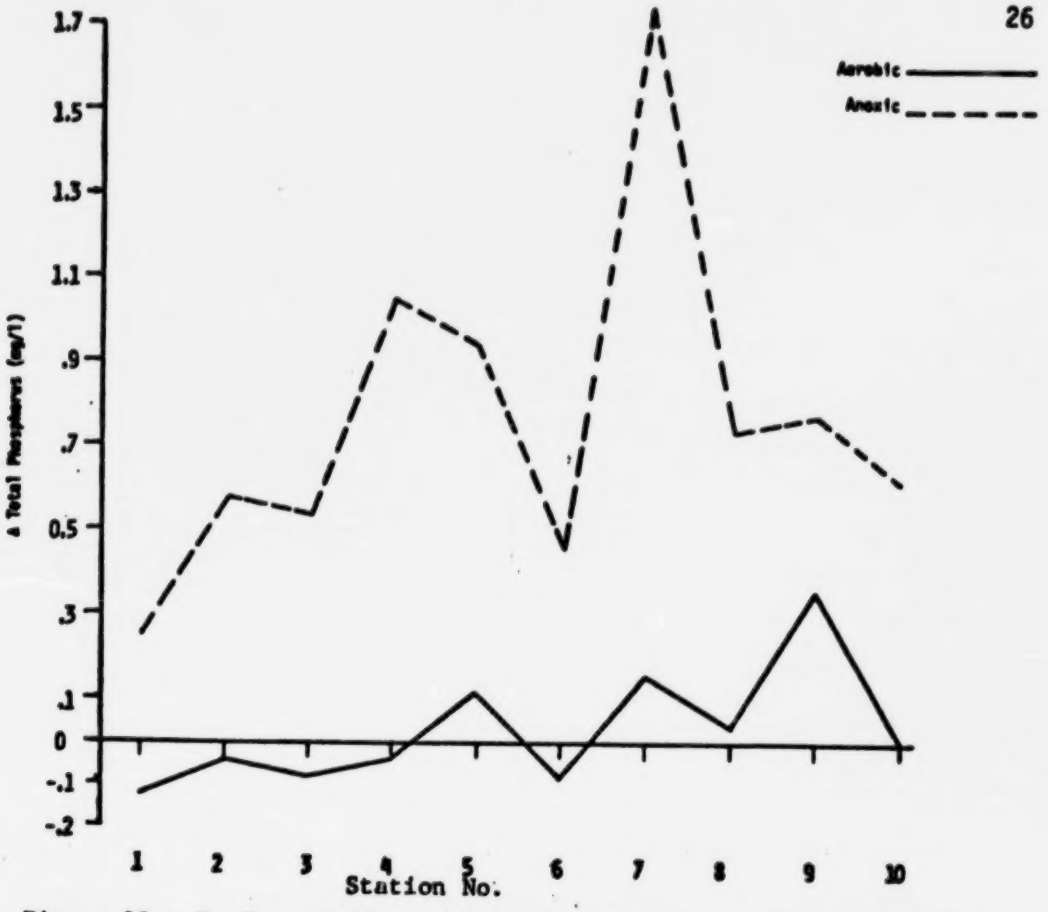

Figure 11. Surface Sediment Nutrient Exchange Δ Total Phosphorus 6-day exposure

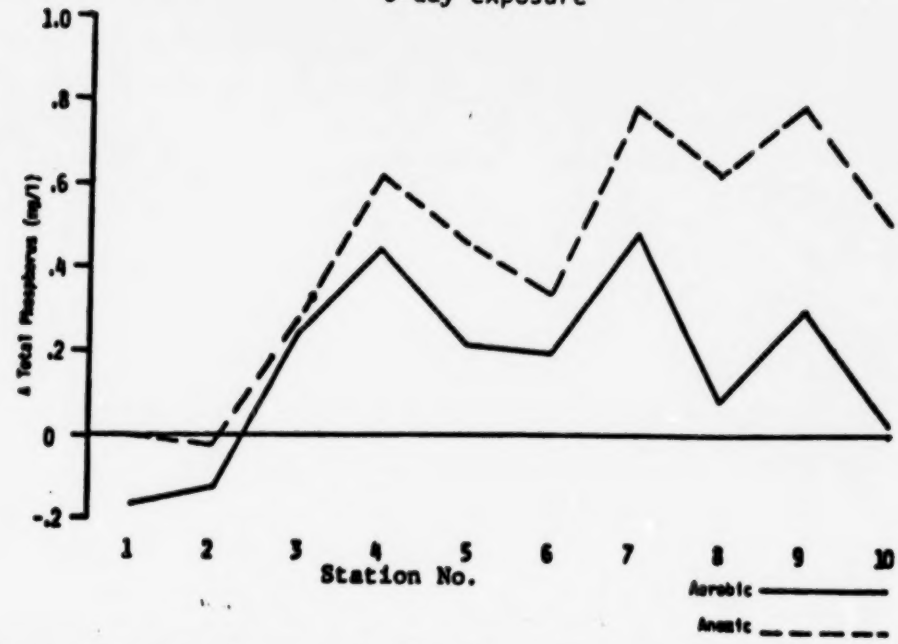

Figure 12. Underlying Sediment Nutrient Exchange Δ Total Phosphorus 6-day exposure

The nutrient exchange characteristics for total phosphorus and orthophosphate were very similar [Table 4]. Under aerobic conditions the underlying sediments generally released greater quantities of total phosphorus than surficial sediments [Fig. 13]. This occurred even though surficial sediments were shown to have higher initial concentrations of phosphorus [Table 3]. This probably was a result of the different physical properties of the sediments. The unconsolidated nature of the surficial sediments is conducive to more thorough aeration than will occur in the dense clay of underlying sediments. This increased aeration will allow the iron component of the sediment to remain in the oxidized (Fe^{+3}) state, thus immobilizing phosphorus. Lack of penetration of oxygen into the underlying sediment layers would permit anoxic sediments to form, resulting in a reduced iron state (Fe^{+2}) and subsequent release of orthophosphate from the sediment. A similar situation would be expected to occur in the natural sediment beds in the estuary if surficial sediments were removed by dredging.

Under anoxic conditions, exchange of phosphorus was predictable; total phosphorus was released in greater concentrations from surficial sediments [Fig. 14]. Essentially all phosphorus migration was in the form of orthophosphate [Table 4]. The most important aspect of orthophosphate migration was that average net concentrations released from anoxic surficial sediments was about 1,800% greater than the average orthophosphate released from aerobic surficial sediments. The average net concentration for underlying sediments was approximately 180% greater under anoxic conditions. This indicates surficial sediments have a much greater potential to stimulate algal growth if anoxia occurs.

These nutrient data indicate that if the algal crop in the Back River Estuary is growth limited by nitrogen, anoxic conditions occurring in the water column would have little stimulating effect on algae production. This is because ammonia, the major nitrogen source in the estuary, is generated from the sediments at a rate largely independent

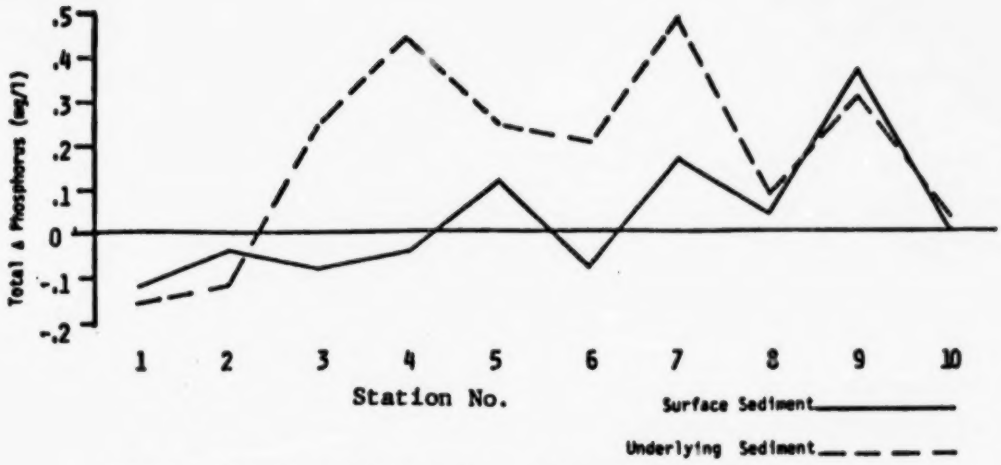

Figure 13. Aerobic Nutrient Exchange Δ Total Phosphorus
6-day exposure

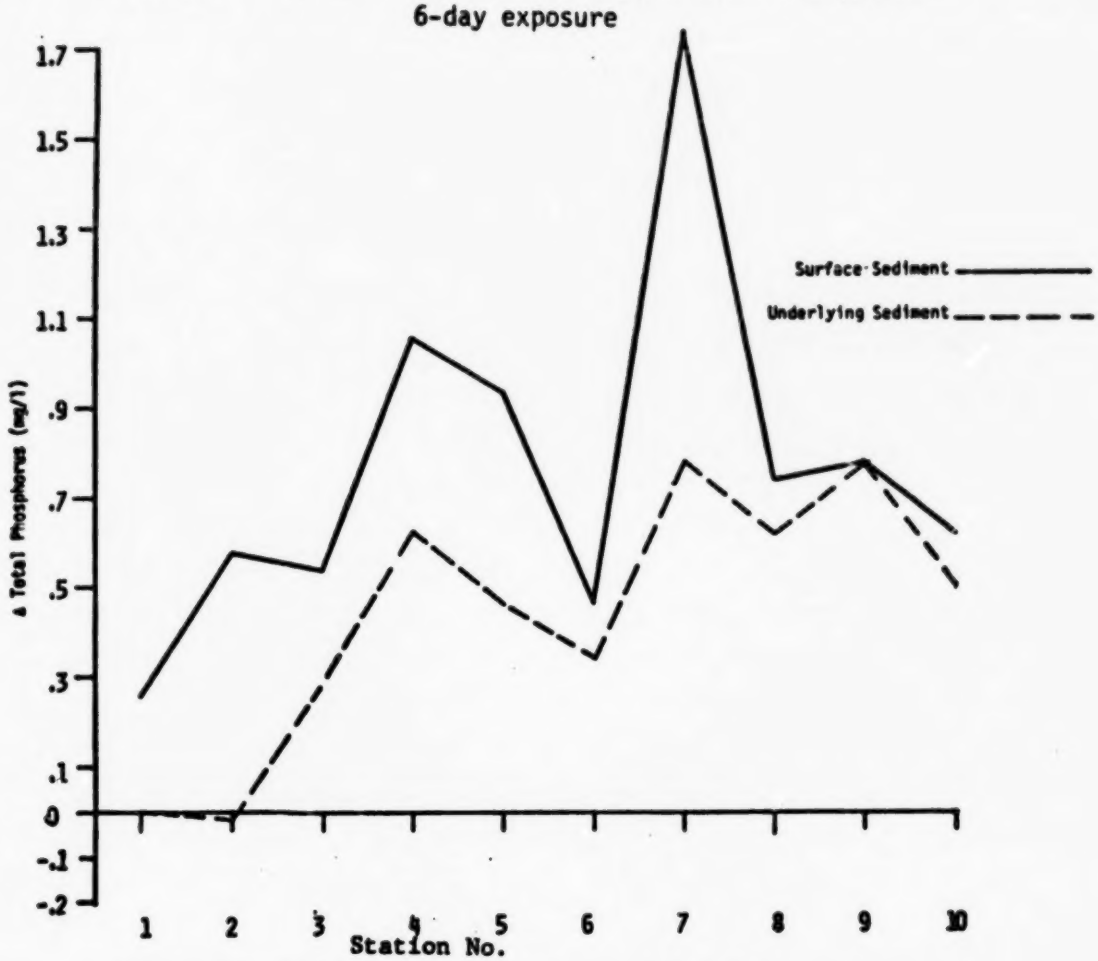

Figure 14. Anoxic Nutrient Exchange Δ Total Phosphorus
6-day exposure

of aerobic and anoxic conditions. However, if the algae are growth limited by phosphorus, as is most often the case,[6] anoxic conditions capable of increasing orthophosphate levels could have a growth stimulating effect.

Improvement of the water quality in the Back River Estuary is primarily a problem of maintaining adequate dissolved oxygen levels in the overlying water column, particularly in the area represented by stations 1 to 4. To accomplish this, SOD must be reduced and excessive algal growth controlled by limiting available nutrients.

Since the Baltimore Back River WWTP is reported to be the principal source of high SOD and nutrient loading in the estuary, diversion of or nutrient removal from the effluent discharge is essential. Diverting the outfall would involve a one-time monetary investment, whereas, nutrient removal requires continual capital expenditure and constant maintenance. From a practical and economic viewpoint, effluent diversion is the logical choice.

Dredging surficial sediments would not effectively reduce nutrient loading. Nutrient exchange tests indicated that the nutrient loading potential of surficial and underlying sediments were similar under aerobic conditions. Phosphorus levels were high in surficial sediments, but in an aerobic environment orthophosphate migration was effectively immobilized. The existing surficial sediments exert a greater SOD on the water column than the underlying sediments. However, this is primarily due to the continual discharge by the Baltimore Back River WWTP of an effluent high in settleable solids and biochemical oxygen demand (BOD). If this discharge is discontinued, the SOD of surficial sediments would be expected to be met and subsequently stabilize to a rate similar to that of the current underlying sediments.

Removal of surficial sediments to reduce the SOD in the estuary is not advisable and could in itself pose a serious environmental problem. Specifically, removal of 1.5 m of sediment would double the volume in most portions of the estuary. Flow velocities, particularly in the western half of the estuary, may be too low to adequately flush an area of such increased volume, and stagnation could occur. Stagnation of this portion of the estuary could produce conditions more conducive to algal bloom and related fish kills than currently exist.

VI. METHODS

CORE SAMPLING

Core samples were removed using a 3.6 m polyvinyl chloride coring tube of 10 cm bore. The tube was manually inserted through the soft surface sediments and approximately 1 m into the underlying sediment. It was possible to remove the tube by capping only the top, the dense underlying clay forming an effective plug for the bottom. Upon removal of the upper cap, gravitational force was sufficient to initiate core extrusion, providing an undisturbed sample about 2 m long. In areas where water depth exceeded 2 m, the coring tube was inserted and retrieved by the NEIC diving team using SCUBA equipment.

IN-SITU SEDIMENT OXYGEN DEMAND TEST

Sediment oxygen demand rates were estimated from changes in the dissolved oxygen concentration of water sealed in a clear plexiglass chamber [Fig. 15]. The prism-shaped chamber is constructed to maximize the ratio of bottom area to volume while allowing the circulating system to be sufficiently far from the bottom to prevent roiling of the sediments. The chamber is bolted to a stainless steel flange, with cutting edges, which effectively seals water within the chamber when lowered onto soft bottom sediments. A check valve is attached to one corner to permit removal of entrapped gases prior to starting the test. The chamber enclosed 0.186 m^2 of bottom sediment and 12 liters (0.012 m^3) of overlying water. Water was circulated within the chamber by means of a 12V submersible pump. To insure that an effective seal was maintained, a salt (NaCl) solution was injected into the system which increased the

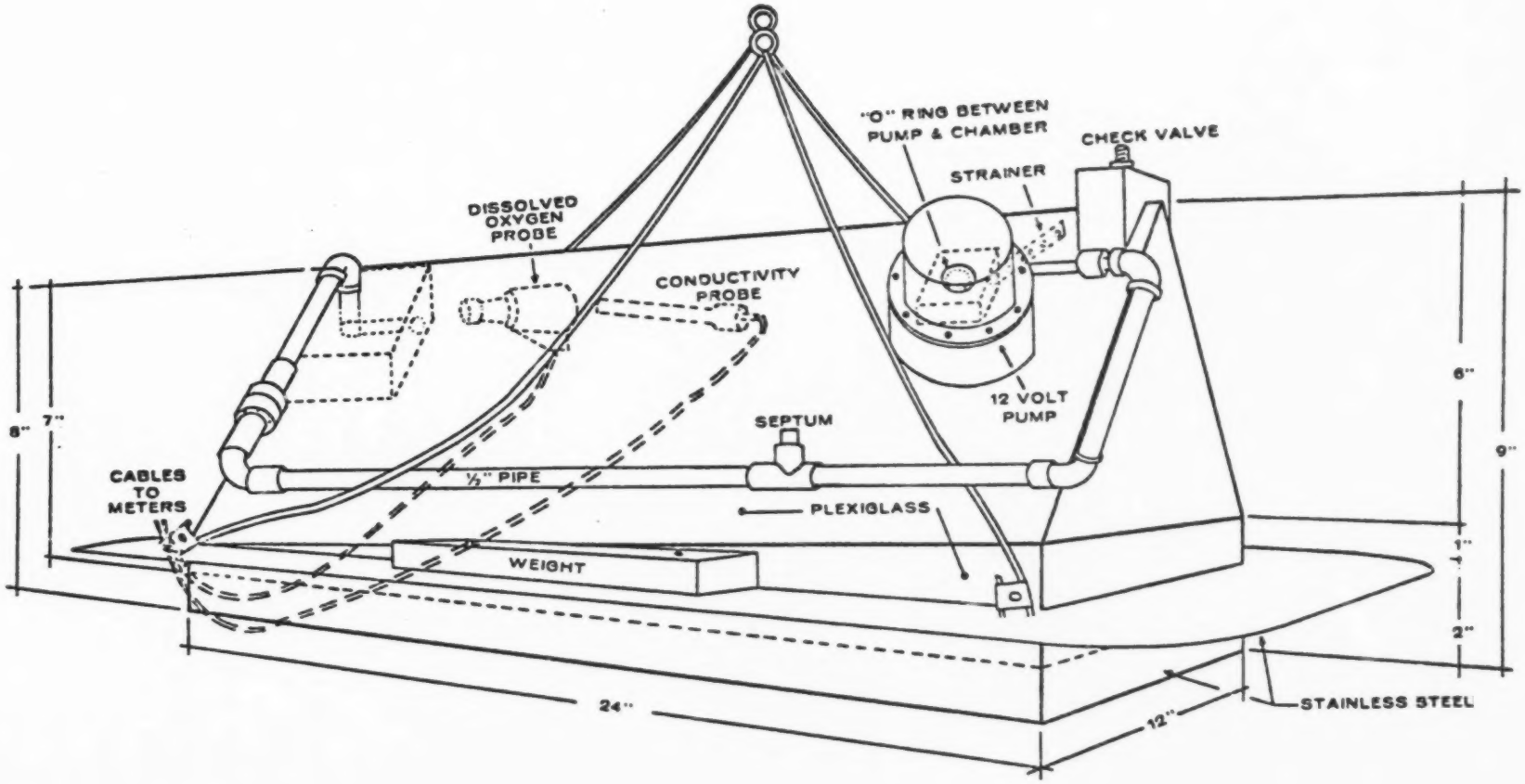

Figure 15. Sediment Oxygen Demand Chamber

specific conductance of the entrapped water. The increased conductivity was then monitored throughout the test. Changes of dissolved oxygen within the chamber were measured with a portable dissolved oxygen meter and were recorded at 5-minute intervals.

Each test was conducted for 30 minutes or until a 1 mg/l decrease in dissolved oxygen was observed. Rates were measured in duplicate at each station. Clear BOD bottles containing near-bottom water were incubated approximately 0.3 m above the bottom sediment to estimate dissolved oxygen changes due to the water itself. The oxygen demand rate of the chamber was adjusted to account for this change where necessary.

The following calculation was used to estimate SOD rates:

$$SOD = \frac{(Ci - Cf)V}{tA}$$

where

SOD = sediment uptake rate in grams $O_2/m^2/day$

V = volume of confined water in m^3 (0.012)
A = bottom area within chamber in m^2 (0.186)
t = test period in days
Ci = initial dissolved oxygen in chamber in mg/l
Cf = final dissolved oxygen in chamber in mg/l

LABORATORY SOD TEST

Sediments for laboratory SOD test were obtained by core sampling. With as little disruption as possible, one liter of sediment was removed from the uppermost and lowermost segments of the core. The sediment sample was evenly distributed over the bottom of plastic cylindrical

containers. The sediment was then covered with 8 liters of unfiltered water drawn at station 8. An airtight cap was placed over the container with care taken to allow no air pockets to develop. Dissolved oxygen concentrations were measured at 5-minute intervals for at least 1 hour. Circulation was accomplished by use of an agitating dissolved oxygen probe fitted through the cap with an airtight seal.

Estimation of SOD rate was calculated using the same formula as in the in-situ tests and was expressed as grams $O_2/m^2/day$.

NUTRIENT INTERCHANGE TESTS

Nutrient interchange tests were done on surface and underlying sediments from 10 sampling stations under aerobic and anoxic conditions. Sediments were obtained by core sampling.

One liter of sediment was evenly distributed over the bottom of a 9-liter opaque plastic container [Fig. 16] and covered with 6 liters of water obtained at mid-channel at station 8. For anoxic tests, dissolved oxygen was removed from the water by nitrogen gas sparging for 5 hours prior to starting the test. The containers were then blanketed with nitrogen and sealed with airtight caps. Dissolved oxygen concentrations were held at near saturation levels for aerobic tests by continuous aeration.

To assure that stable conditions were maintained during the testing period, water in the containers was monitored daily for pH, temperature, specific conductance and dissolved oxygen. Water samples (50 ml) were removed at 24-hour intervals for six days, preserved on ice, and delivered immediately to the Maryland WRA laboratory in Annapolis for nutrient analysis.

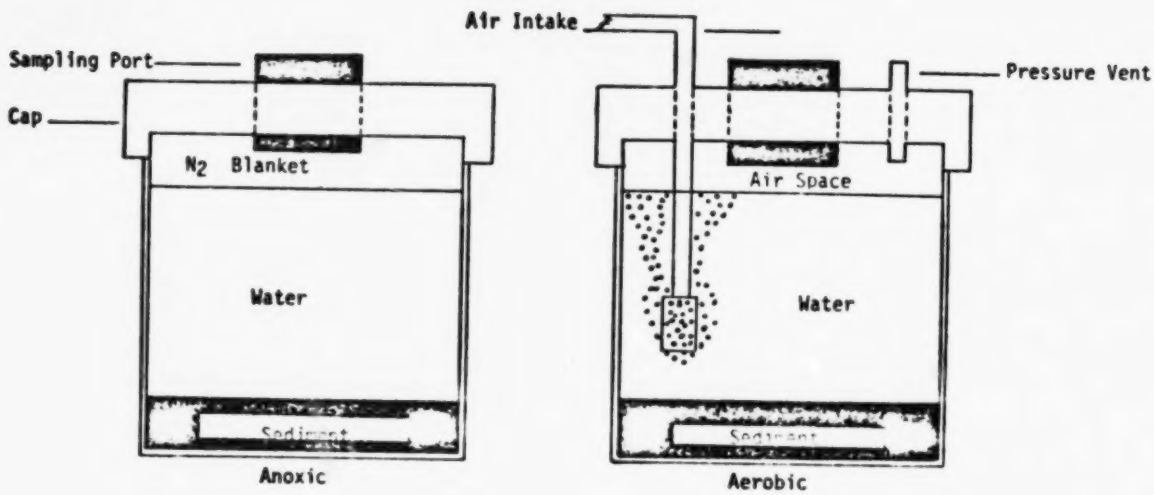

Figure 16. Nutrient Interchange Chambers

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